High-Speed Shadowgraph Visualisation of Flow in a Miniature Hydrogen-Fuelled Valveless Pulsejet Engine

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Valveless pulsejet engines are viable propulsion devices for MAVs. Since no accepted design methodologies are available for such propulsors, except for empirical rules, it is essential that a deep knowledge of the complex flow phenomena within such engines is gathered so as to evolve sound designs. An experimental study has been carried out to understand the unsteady acoustically coupled combusting flow phenomena in a hydrogen fuelled inline intake miniature valveless pulsejet engine. The engine chosen for the experiment was a 2D model which was little more than pen size. A novel way of allowing optical access in constructing a 2D valveless pulsejet by sandwiching three metal plates of predesigned shape in-between the two quartz glass panes was adopted. The model was fabricated in such a way that Schlieren / shadowgraph high-speed visualisation could be employed in capturing the unsteady flow structures of the complete engine including the regions around the intake and the exhaust. The unsteady acoustically coupled combustion and flow fields at the intake and the exhaust and inside the engine were simultaneously captured by using a FASTCAM PHOTRON SA4 monochrome high-speed camera. Time resolved shadowgraph images revealed that coupled flow structures at the inlet, within the combustion chamber and the tail pipe were essential for the stable operation of the pulsejet engine.

Introduction

Currently, MAVs employ electrically driven propellers for propulsion. These systems have the twin disadvantages of limited range, depending on the battery capacity and the supplies are not secure as the complete units are still imported. Air breathing propulsion systems such as pulsejets are viable alternatives as they allow good range and can be indigenously developed. Pulsejets unlike ramjets have static thrust too. MAVs are currently being considered for the following two applications :-

(i) Reconnaissance, for which the stealth quality of low noise emission is essential. For such an application, the pulsejet engine could be embedded within the MAV. In addition, its dominant noise emission frequencies can be increased to approach those beyond the level of human hearing, by shortening its acoustic length. Multiple units may be necessary to maintain the thrust. By coupling the units to a common inlet and exhaust plenums, noise cancellation may be made more effective. This arrangement will approach that for distributed propulsion and if necessary, smart deflector vanes can be positioned at the engine exhaust to allow vectoring of the engine thrust for better MAV maneuverability. (Fig 1 a,b,c & d)

(ii) To prevent bird strike at airports. In such applications, the pulsejet can be mounted outside the MAV and in addition its exhaust length can be chosen to create noise emission at frequencies close to what makes the birds uncomfortable. (Fig 1 e.)

Hence, it is essential, that the flow phenomena within the pulsejet engine should be clearly understood to make the necessary design changes.

A valveless pulsejet engine is a simple propulsion device that does not have any rotating parts. This propulsion device has the advantage of scaling from large sizes to miniature sizes which find applications as thermo acoustic propulsion systems for MAVs. Although the pulsejet engine construction appears to be simple, the flows and the combustion processes that occur within are highly coupled. They involve three dimensional, turbulent transient combusting flow fields, variable physical properties, acoustic pressure fields and large transient energy releases. Modern photographic methods supported by non-intrusive flow visualization techniques help in understanding the unsteady combusting flow structures in such engines, thereby enhancing the knowledge base, which will ultimately help in arriving at better modeling and hence evolve a strong design methodology. A pulsejet engine consists of an intake, combustion chamber and a tail pipe and to get a clear idea of the entire flow/flame structures, it is essential that the unsteady acoustically coupled flow field at critical regions of the pulsejet need to be captured simultaneously.

This paper reports the results of high-speed shadowgraph visualisation of the combusting flow in an ingeniously constructed miniature hydrogen fuelled valveless pulsejet engine. By this method, the unsteady coupled flow structures within the entire engine including the region at the inlet and the exhaust have been simultaneously captured and studied to reveal their importance in achieving stable operation of the valveless pulsejet engine.

Engine model and experimental setup

A 2D pulsejet engine was constructed in an ingenious way with optical access so that the entire flow structure of the engine could be made visible. This was made possible by sandwiching three metal plates of predesigned shape in-between the quartz glass panes in such a way that Schlieren / shadowgraphs could be employed for capturing the unsteady combusting flow field of the complete engine including the regions around the intake and the exhaust. Fig. 2 shows a schematic of a valveless pulsejet engine. It basically consists of intake duct, combustion taper with a taper duct connecting the exhaust duct.

Fig 3 shows the dimensions and construction of the engine. The inlet section dimension was 4 x 7.2 x 18 mm, the exhaust length was 9 x 7.2 x 120 mm and the combustion chamber was 7.2 x 18 x 18 mm with a taper duct length 30 mm length joining the combustion chamber and the tail pipe. The model had top and bottom plates of 3 mm thickness cut in the predesigned shape and by assembling with suitable gasket, quartz glass side windows of 3 mm thick the plates were held together with the flange plates which had provisions to insert the studs. By this novel technique it was possible to arrive at a 2D geometry of the pulsejet engine with a completely transparent window to visualize the flow structures inside the engine. Fig. 4 shows a photograph of the assembled engine model.

The gaseous hydrogen was fed into the combustion chamber through a 0.8 mm diameter choked orifice and was positioned at 27 mm from the inlet. The hydrogen gas was fed to the injector from a gas cylinder using a SWAGELOCK regulator at an upstream pressure, always maintained at 0.35 MPa. The fuel line had a non-return valve and flame arrester and the fuel flow was controlled using a SWAGELOCK 6 mm diameter needle valve. A water-cooled KULITE pressure transducer, flush mounted on the combustion chamber wall, captured the unsteady pressure signals. All the data were recorded using a NATIONAL INSTRUMENTS computer based data acquisition system. Fig. 5 shows a schematic of the test setup and the engine mounted on the test stand.

Experimental procedure and results

The conventional way of starting a pulsejet engine is to ignite the fuel and push in a puff of compressed air to aid the mixing of the fuel and create the necessary turbulence for starting the pulsating combustion. The engine starts to resonate and operate in self sustained mode, only when the heat addition is in phase with the pressure inside the engine. In the present setup the ignition of the hydrogen that was fed into the engine was achieved by an external flame torch. A small amount of pressurized air was pushed through intake duct to initiate the pulsations. Fig 6 shows the hydrogen fuelled pulsejet in operation. Typical fuel flow rate of 4 g/min was used during the experiment. Fig. 7 shows the engine mounted on the test stand and a typical test result showing the unsteady combustor wall pressures and the corresponding FFT indicating the dominant frequency to be around 970 Hz which correspond to an acoustic pulsejet engine length of around 120 mm.

Flow visualisation studies

A high speed camera PHOTRON FASTCAM SA4, was used to capture the unsteady flow patterns. Two collimating mirrors of 300 mm diameter and a focal length of ~2.8 m were used for the shadowgraph studies. Fig. 8 shows the conventional Z type mirror arrangement used for the flow visualisation studies. Fig. 9 shows the photograph of the arrangement. Fig. 10 shows time resolved frames of the coupled flow structures of the complete engine including the inlet and exhaust. The flow structures clearly indicate the nature of the intermittent combustion events that were happening inside the pulsejet engine. The packets of combusted gases being thrown out in pulses at the inlet and the exhaust are clearly visible. The formation of the toroidal vortices because of the relative velocity gradient that exists with respect to the outside air both at the inlet and exhaust have been visually captured. The ejection phase of the pulsations and the suction phase are also visible in the flow patterns. The sucking of the hot gases back from the tail pipe into the engine because of the "Kadenacy effect " is clearly visible in the time resolved frames of the flow near the tail pipe. This clearly shows that the fresh fuel air mixture that is present in the combustion chamber during the suction phase gets ignited by the hot residual gases present because of the reverse flow.

Results and discussions

Miniature inline intake valveless pulsejet engines a little more than a pen size were designed, fabricated and tested successfully. A novel way of constructing a 2D valveless pulsejet by sandwiching three metal plates of predesigned shape in-between the two quartz glass panes was designed and fabricated in such a way that Schlieren / shadowgraph could be employed in capturing the combusting flow structure of the complete engine including the regions around the intake and the exhaust. Time resolved shadowgraph images revealed the essential coupled flow structures at the inlet, combustion chamber regions and the tail pipe region. The flow patterns in the model clearly indicated the presence of toroidal vortices both at the inlet and the exhaust of the engine. The ejection phase and the suction phase of the pulsations of the unsteady combustion were also captured. This study has given a clear understanding of the operation of a valveless pulsejet engine, in particular, the essential coupling of the intake, combustor and exhaust flows. The sizing of the engine has to be such as to allow this coupling.

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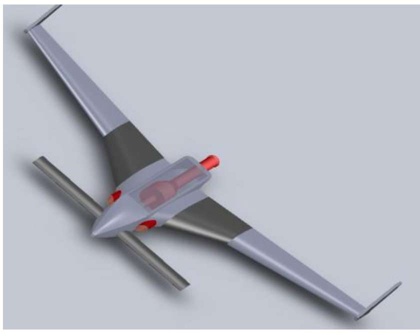
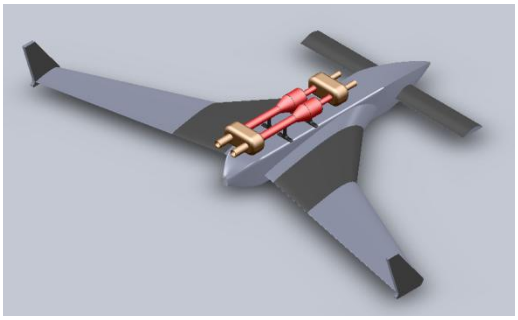
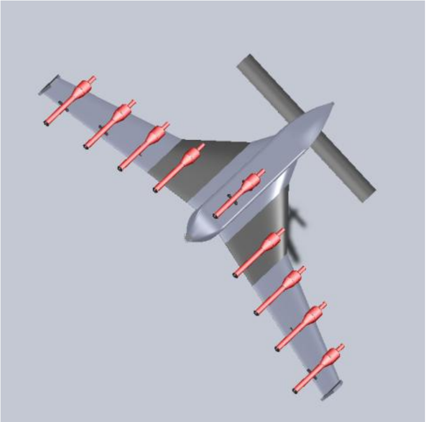
The authors also extend their heartfelt thanks to Mr C Satish , Project Assistant of the Propulsion Division.



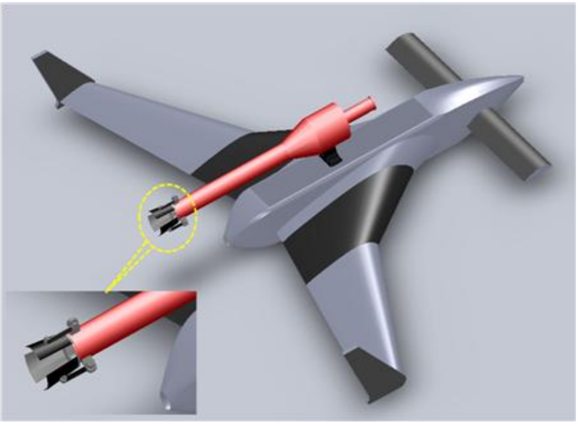
(a) Stealth



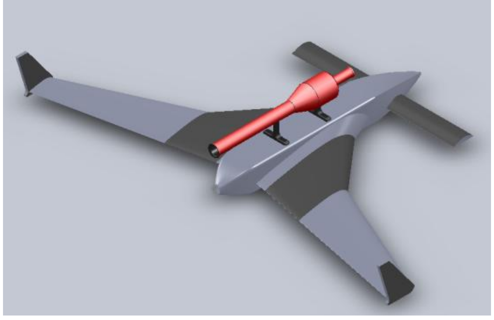
(b) Noise attenuation



(c) Distributed Propulsion



(d) Thrust Vectoring



(e) Bird Strike

Fig. 1 Typical valveless pulsejet engine configurations for various applications

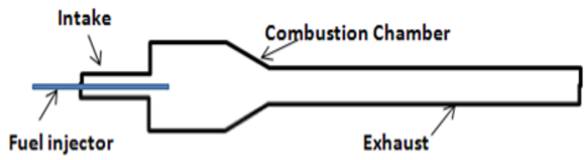


Fig 2. Valveless pulsejet engine (Schematic)

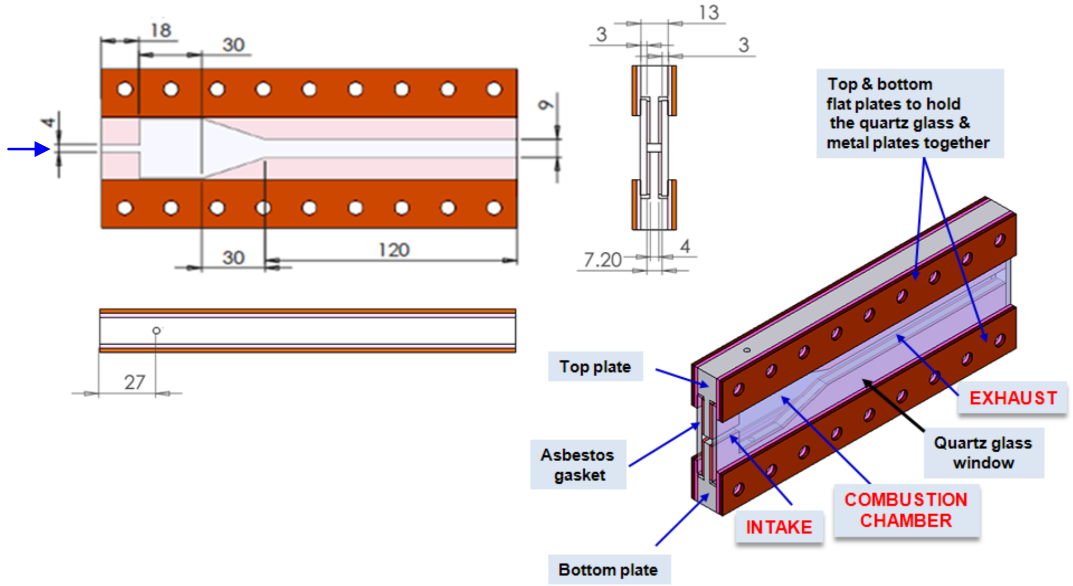


Fig.3 CAD model and construction of the 2D valveless pulsejet engine with an optical window for flow visualisation.

Fig. 4 Assembled 2D valveless pulsejet engine

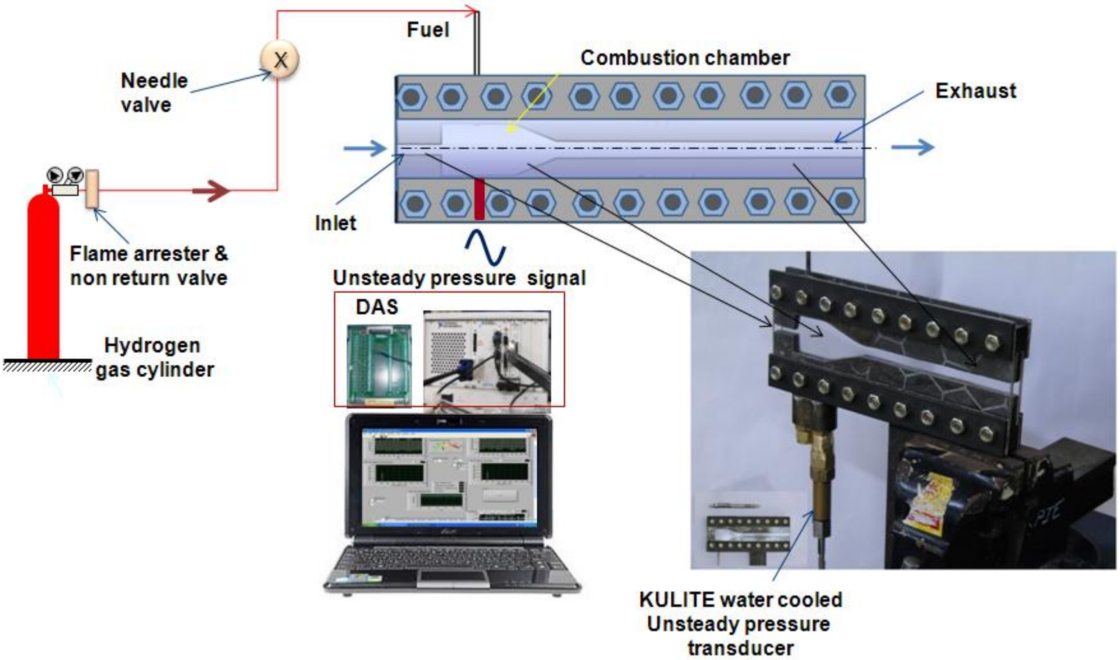


Fig. 5 Schematic of the hydrogen fuelled valveless pulsejet engine test setup and the engine mounted on the test stand.

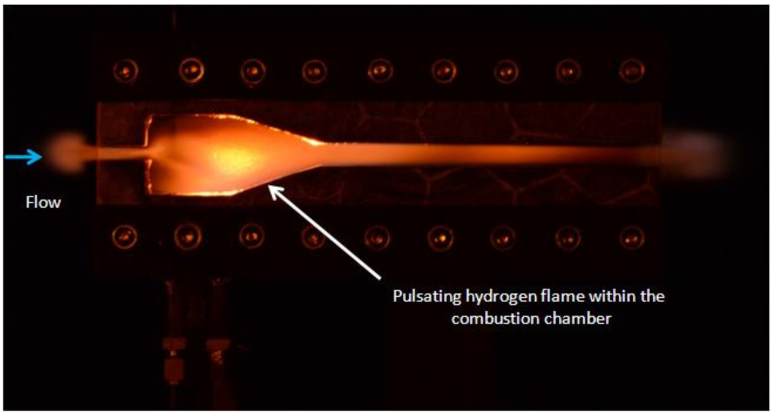


Fig. 6 Hydrogen fuelled 2D valveless pulsejet engine in operation

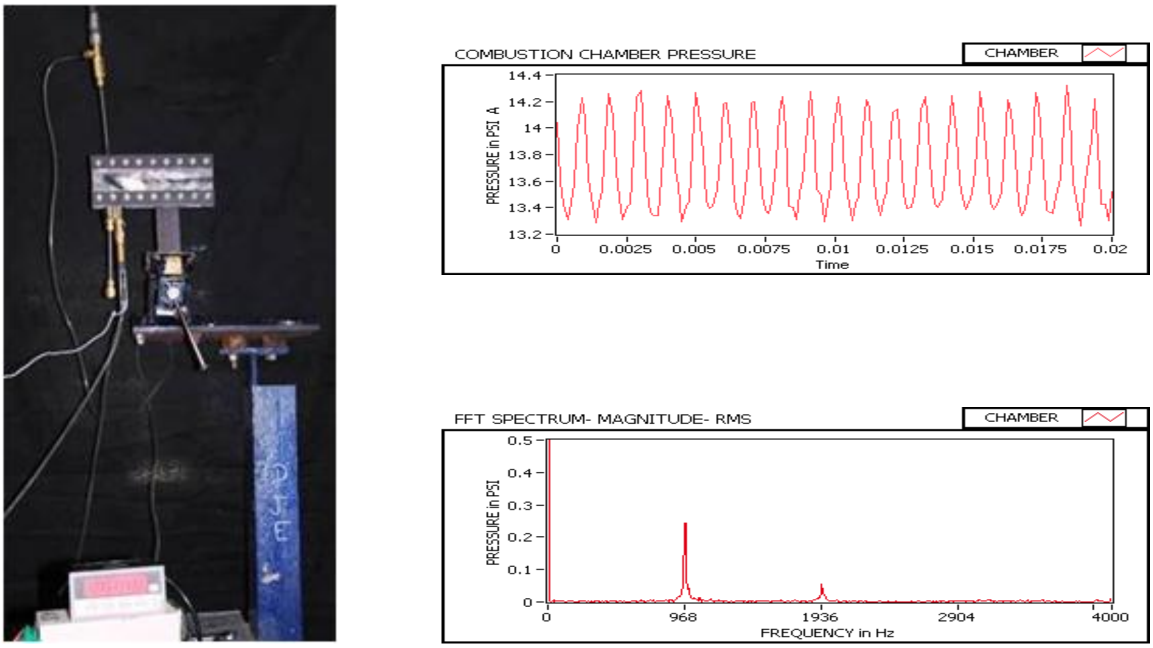


Fig. 7. 2D Valveless pulsejet engine mounted on test bench and a typical test result showing the unsteady combustion chamber wall pressure signals and the corresponding FFT for a typical fuel flow rate of 0.004 kg/min

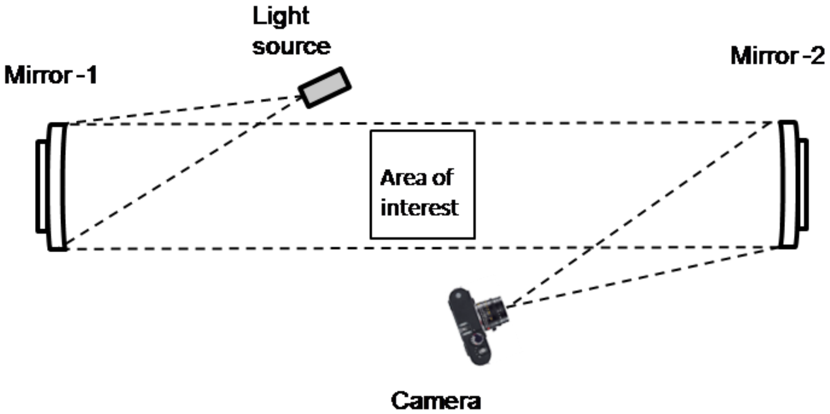


Fig.8. Schematic test setup of the shadowgraph arrangement

Fig.9 Photograph of the shadowgraph arrangement

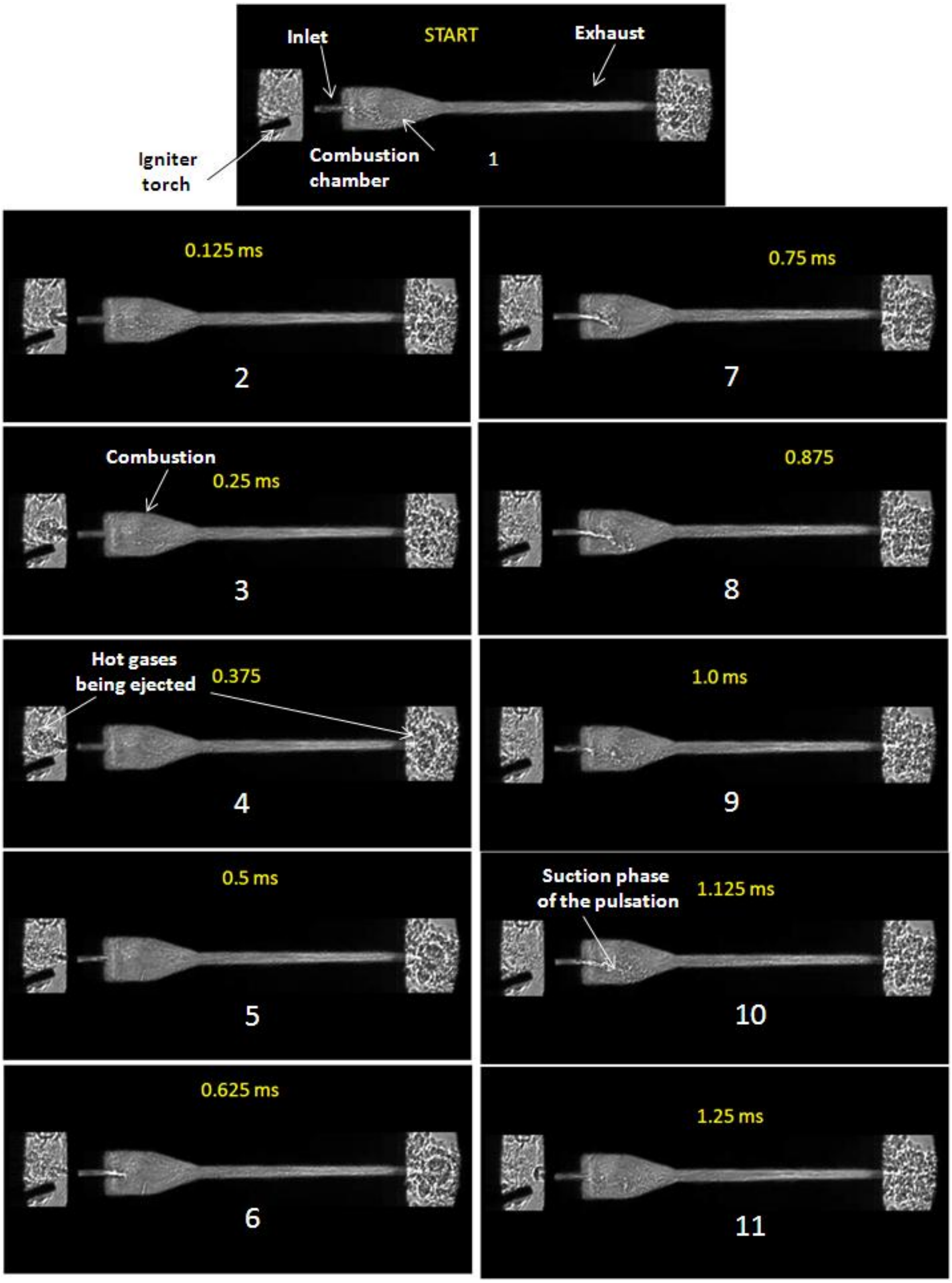


Fig.10. Time resolved frames showing the flow field of the complete 2D engine captured at 40000 frames per second